AN ARMA/GARCH BASED APPROACH FOR STRUCTURAL DAMAGE DETECTION

Ling Yu[1, 2 a)], Cong Cheng[1, 2] & Liujie Chen [1-3]

[1] *Department of Mechanics and Civil Engineering, Jinan University, Guangzhou 510632, China*

[2] *MOE Key Laboratory of Disaster Forecast and Control in Engineering, Jinan University, Guangzhou 510632, China*

[3]*Department of Applied Mechanics and Engineering, Sun Yat-Sen University, Guangzhou 510080, China*

Summary A novel approach is proposed for structural nonlinear damage detection based on a model of autoregressive moving average and generalized autoregressive conditional heteroscedasticity (ARMA/GARCH) in this paper. A new nonlinear damage-sensitive feature (DSF) is defined as ratio of conditional standard deviation of residual error of GARCH model in the reference state and in the unknown state, respectively. The performance of the proposed approach is then verified by 5-channel measured acceleration response data of a three-story frame structure provided by Los Alamos National Laboratory (LANL), USA, in which nonlinear damages were introduced through nonlinearities resulting from impacts with a bumper. The illustrated results show that the proposed method can effectively estimate extent of nonlinear damage with higher accuracy and less computational cost, which makes it applicable for structural damage detection in the field.

INTRODUCTION

In recent years, the structural damage detection, a major part of the structural health monitoring (SHM) system, has been most commonly investigated in many ways and algorithms. Most of these methodologies employ vibration data by using one or a combination of different time domain and/or frequency domain algorithms to extract features that will be sensitive to the changes occurring in the structure and relatively insensitive to other interfering effects. One common approach to extract damage sensitive features (or damage features) from SHM data is to use time series analysis [1]. These methodologies usually make use of AR (Auto-Regressive), ARX (Auto-Regressive models with eXogenous outputs) and/or ARMA (Auto-Regressive Moving Average) models to detect the damage in a statistical manner [2-4]. However, all of studies mentioned above are based on linear AR, ARX or ARMA model and assumed the residual error obeys the normal distribution. This assumption often increase misdiagnosis rate because the damage information mainly focused on the tails of distribution where some slight deviations from the normal condition can be seen. The states with the nonlinearities show that an assumption of normality is not justified [5]. To resolve the mentioned problems, this study employs the ARMA/GARCH (which has been successfully used in the econometrics field [6]) model as an excellent approach for structural damage detection. Where the ARMA and GARCH models has been proved that they can be used to recognize the determined mean part and fluctuant part of vibration data for the wear and fault condition of machine [7] because the GARCH models consider the moments of a time series as variant (i.e., the error term: real value minus forecasted value does not have zero mean and constant variance as with an ARMA process).

BACKGROUD KNOWLEDGE OF NOVEL APPROACH

This study applies the ARMA/GARCH model in evaluating the current and future states of structural condition and also applies in the SHM domain in which each advance of ARMA and GARCH model will be exploited to describe the damage condition of the structure, respectively. The ARMA/GARCH model for the variance model can be summarized in the following equations:

$$y_t = c + \sum_{i=1}^{r} \phi_i y_{t-i} + \sum_{j=1}^{m} \theta_j \varepsilon_{t-j} + \varepsilon_t, \quad \varepsilon_t \sim N(0, \sigma_t^2) \tag{1}$$

$$\sigma_t^2 = k + \sum_{i=1}^{p} G_i \sigma_{t-i}^2 + \sum_{j=1}^{q} A_j \varepsilon_{t-j}^2 \tag{2}$$

$$\varepsilon_t = \sigma_t z_t, \quad z_t \sim N(0,1) \tag{3}$$

Eq. (1) is the general linear ARMA(*r, m*) model. Where y_t is the time series needed to be modeled, *c* is a constant, *r* is the number of autoregressive orders, *m* is the number of moving average orders, ϕ_i is autoregressive coefficients, θ_j is moving average coefficients and ε_t is the residual error. In Eq. (1), the error term ε_t, i.e., innovations, is the random component, which is commonly assumed to be zero mean and constant variance. However, for some practical time series, ε_t do not satisfy the homoscedastic assumption of constant variance. The time-varying variance, i.e., volatility or heteroscedasticity, which depends on the observations of the immediate past, is called conditional variance. The

a) Corresponding author. Email: **Lyu1997**@163.com**.**

conditional variance of the innovation ε_t, σ_t^2 is defined as $\sigma_t^2 = Var_{t-1}(\varepsilon_t) = E_{t-1}(\varepsilon_t^2)$. Eq. (2) is the general GARCH (p, q) model for the conditional variance of innovations ε_t with constraints $\sum_{i=1}^{p} G_i + \sum_{j=1}^{q} A_j < 1, k > 0$, $G_i \geq 0 (i = 1,2,..., p)$, $A_j \geq 0 (j = 1,2,...q)$.

EXPERIMENTAL VALIDATION ON NOVEL APPROACH

Some experimental data for a three-story building structure [5] is download from the website of the Los Alamos National Laboratory, USA, and used for evaluating the performance of the proposed approach in this paper. In the structure, a centre column was suspended from the top floor for simulating damage by inducing nonlinear behaviour when it contacts a bumper mounted on the next floor. A load cell (Channel 1) was attached at the end of a stinger to measure the input force from the shaker to the structure. Four accelerometers (Channels 2-5, from the base to the third floor) were attached at the centerline of each floor on the opposite side from the excitation source to measure the system response. The structural conditions were categorized into four main groups. The first group is the baseline condition (Condition 1), in which, the bumper and the suspended column are included in the baseline, but the spacing between the bumper and the column was maintained in such a way that there were no impacts during the excitation. The second group includes the structural conditions with simulated operational and environmental variability (Conditions 2－9). The third group includes the damaged structural conditions simulated by the introduction of nonlinearities into the structure using the bumper and the suspended column with different gaps between them to introduce different degrees of nonlinearity (Conditions 10-14). Finally, the fourth group includes conditions with the simulated damage in addition to the mass changes used to introduce simulated operational variation (Conditions 15-17). There are 10 measured data sets under each condition and are 8192 samples for each data set, respectively. The corresponding DSF are calculated and plotted as following figures.

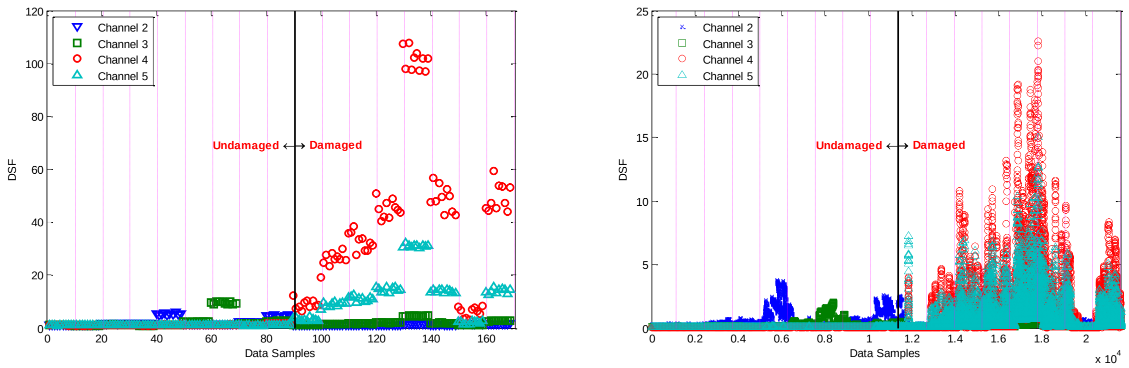

Figure 1. Damage sensitive features using ARMA (left) and GARCH (right) models

CONCLUSIONS

This study proposed a nonlinear novel damage detection approach for systems that operate in a linear manner during normal operation, the applicability of this approach, based on the prediction of the ARMA/GARCH model, has been demonstrated with experimental data and it has been shown to be a reliable way to detect structural damage when it induces transitions from linear to nonlinear response, even in the presence of operational and environmental variability. Moreover, the nonlinear GARCH model can extract more sensitive damage features than the ARMA model from the residual error of the ARMA/GARDH model in the structural reference and unknown states with higher accuracy and less computational cost, which makes it applicable for structural damage detection in situ.

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